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Modeling of Hybrid Solar - Wind Renewable Energy Systems with Battery Storage

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Abstract: One of the major worldwide concerns of the utilities is to reduce the emissions from traditional power plants by using renewable energy and to reduce the high cost of supplying electricity to remote areas. The commonly used renewable sources are solar photovoltaic and wind energy systems have received a great acceptance in field of power generation for pollution free performance, free availability and for great reliability. Further development and effective use of natural resources, the hybrid systems are developed. Hybrid power systems can provide a good solution for such problems because they integrate renewable energy along with the traditional power plants. Hybrid systems are characterized by containing two or more technologies of electrical generation, in order to optimize global efficiency of the processes. Basically this system involves the integration of solar, wind with battery storage device that will gives continuous power. In this Paper, the modeling of hybrid solar photovoltaic and wind energy system with battery storage are done by using MATLAB/SIMULINK software and results are presented.

Keywords: Hybrid Energy system, Wind Energy, Solar Photovoltaic System Battery Storage, MATLAB/SIMULINK.

I. INTRODUCTION

Energy is a vital input for social and economic development of any nation. Renewable energy technologies can help countries meet their policy goals for secure, reliable and affordable energy to expand electricity access and promote development. Renewable energy sources, especially solar and wind energy are likely to play a significant role in providing reliable and sustainable electricity to consumers.

The term hybrid energy system refers to those applications in which multiple energy conversion devices are used together to supply an energy requirement. These systems are often used in isolated applications and normally include at least one renewable energy source in the configuration. In this proposed system solar, wind power system is used for generating power. Solar and wind has good advantages than other than any other non-conventional energy sources. Both the energy sources have greater availability in all areas and it needs low cost. The importance of hybrid systems grown as they appeared to be the right solution for a clean and distributed energy production. In this paper the solar photovoltaic model wind energy systems are modeled by MATLAB/SIMULINK.

II. DISCRTPTION OF HYBRID ENERGY SYSTEM

Hybrid power systems consist on a combination of renewable energy sources such as solar photovoltaic (PV), wind generators etc., to charge batteries and provide power to meet the energy demand, considering the local geography and other details of the place of installation. The design process of hybrid energy systems requires the selection and sizing of the most suitable combination of energy sources, power conditioning devices, and energy storage system together with the implementation of an efficient energy dispatch strategy. The selection of the suitable combination from renewable technology to form a hybrid energy system depends on the availability of the renewable resources in the site where the hybrid systems intended to be installed. In this proposed system solar, wind power with battery storage system is used for generating power. Solar and wind has good advantages than other than any other non-conventional energy sources. Both the energy sources have greater availability in all areas with lower cost.

A. SOLAR ENERGY

Solar energy is that energy which is gets by the radiation of the sun the sun. Solar energy is present on the earth continuously and in abundant manner. Solar energy is freely available. It doesn't produce any gases that mean it is pollution free. It is affordable in cost. It has low maintenance cost. Only problem with solar system it cannot produce energy in bad weather condition. But it has greater efficiency than other energy sources. It only need initial investment. It has long life span and has lower emission. The sun is the original source of almost all the energy used on earth. The earth receives a stock ring amount of energy from the sun, as much energy falls on the planet each hour is the total human's population uses in a whole years.

B. WIND ENERGY

Wind energy is the energy which is extracted from wind. For extraction we use wind mill. The wind energy needs less cost for generation of electricity. Maintenance cost is also less for wind energy system. Wind energy is present almost 24 hours of the day. It has less emission. Initial cost is also less of the system. Generation of electricity from wind is depend upon the speed of wind flowing. Wind energy is a source of renewable power which comes from the air currents flowing across the earth's surface. The wind turbines harvest such kinetic energy and convert it

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into usable power which can provide electricity for home, school, farm, or business applications on small (residential) or large (utility) scales. The growing trends can be attributed to the multi-dimensional benefits associated with wind energy.

C. BATTERY STORAGE DEVICE

The energy storage device is used basically for three purposes, energy stabilization, ride through capability and dispatch ability. The energy stabilization permits the hybrid system to run at a constant stable level with the help of the energy storage devices, even if load fluctuations rapidly. The ride through capability is the capability of energy storage devices which provides the proper amount of energy to loads, when the hybrid system generators are unavailable. Since both wind and PVs are intermediate sources of power, it is highly desirable to incorporate energy storage into such hybrid power systems. Energy storage can smooth out the fluctuation of wind and solar power and improve the load availability. The energy sources like photovoltaic or wind energy systems, the power production depends upon the availability of the resources like sunlight or wind. This makes the nature of power available to loads intermittent, thus making them non-dispatchable sources.

However, the energy storage systems with non-dispatchable energy can be deployed as dispatchable energy sources. Batteries are the basic component of an energy storage system. A battery consists of one or more electrochemical cells that are electrically connected. The basic components of an electrolytic cell like a lead-acid cell are positive electrode, a negative electrode a porous separator and an electrolyte.

During cell operation, ions are created and consumed at the two electrodes /electrolyte interface by oxidation/reductions reactions. The electrolyte, which can either be a solid or liquid chemical, has high conductivity for ions but not for electrons, because if the electrolyte conducts electrons then the battery will self discharge. The hybrid system is shown in Fig. 1. In the following sections, the model of components is discussed.

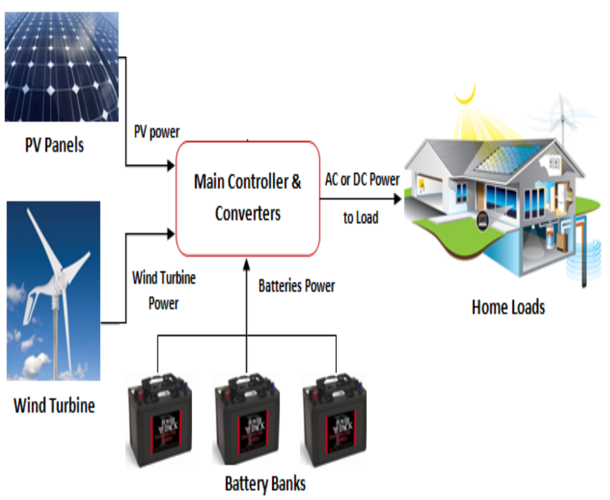

Fig. 1 Block diagram of a hybrid power generation system

III. MATHEMATICAL MODELING OF HYBRID ENERGY SYSTEM

A.MODELING OF PV CELL

The model of the solar PV cell can be realized by an equivalent circuit that consists of a current source in parallel with a diode as shown in Fig. 2 for ideal model Rs, R_p and C components can be neglected.

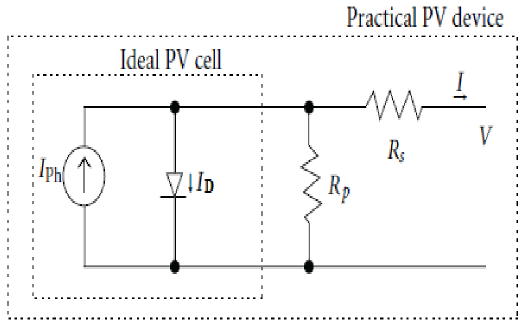

Fig. 2 Equivalent circuit diagram of a solar pv cell

The diode is the one which determines the current-voltage characteristic of the cell. The output of the current source is directly proportional to the light falling on the cell. The open circuit voltage increases logarithmically according to the Shockley equation which describes the interdependent of current and voltage in a solar cell. An equation that represents I -V characteristics of a solar array is given by the following mathematical equation as: The power output of a single diode solar cell is given by (Villalva et al. 2009)

$$P = VI \text{ ---------- } (1)$$

The photocurrent (I_{ph}) which mainly depends on the solar irradiation and cell temperature is described as (Villalva et al. 2009):

$$I_{ph} = [\mu_{sc}(T_c - T_r) + I_{SC}]S \text{ --------- } (2)$$

Where μ_{sc} is the temperature coefficient of the cell's short circuit current; Tr is the cell's reference temperature; Isc is the cell's short circuit current at a 25°C and 1kW/m^2; and S is the solar irradiation in kW/m^2. Furthermore, the cell's saturation current (Is) varies according to the cell temperature and can be described as (Villalva et al. 2009).

$$I = I_{ph} - I_s\left(e^{\frac{q(v+IR_s)}{mkT}} - 1\right) - [\frac{V+IR_s}{R_p}] \text{----} (3)$$

Equation (3.1) is used in computer simulations to obtain the output characteristics of a solar cell. To simulate the selected PV array, a PV mathematical model having N_P cells in parallel and N_s cells in series is used according to the following equation (neglecting shunt resistance):

$$I = N_P I_{ph} - N_P I_S\left(e^{\frac{q(v+IR_S)}{(mkT\ N_S)}} - 1\right) \quad \text{----- } (4)$$

Assuming N_P the above equation can be rewritten as:

$$I = I_{ph} - I_S\left(e^{\frac{q(v+IR_S)}{(mkT\ N_S)}} - 1\right) \quad \text{----- } (5)$$

In particular, the cell reverse saturation current, Is, varies with temperature according to the following equation as:

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$$I_S = I_{S(T_1)} * \left(\frac{T}{T_1}\right)^{\frac{3}{m}} * e^{\frac{-qv}{mK}}\left(\frac{1}{T}-\frac{1}{T_1}\right) \text{ -------- (6)}$$

$$I_{S(T_1)} = \frac{I_{SC\,(T_1)}}{(e^{qvoc\,(T_1)/mK\,T_1 - 1})} \text{ --------- (7)}$$

The photo current I_{ph}, depends on the solar radiation (S) and the temperature (T) according to the following equation as:

$$I_{ph} = I_{ph(T_1)}(1 + K_0(T - T_1)) \text{ -------(8)}$$

$$I_{ph(T_1)} = S * I_{SC(T_1,norm)}/S_{norm} \text{ --------(9)}$$

Where $K_0 = (I_{S(T_2)} - I_{S(T_1)})/(T_2 - T_1)$------(10)

The series resistance of the cell is given as

$$R_S = \frac{dV}{dI_{voc}} - \left(\frac{I}{X_V}\right) \text{--------- (3.9)}$$

Where $X_V = I_{0(T_1)} * q/mKT_1 * (e^{qvoc\,(T_1)/mK\,T_1}$ --- (11)

The PV power, P, is then calculated as follows

$$P = N_P I_{ph} V - N_P I_S V\left(e^{\frac{q(v+IR_S)}{(mkT\,N_S)}} - 1\right) = VI \text{ ----- (12)}$$

where
V - output voltage of PV module,
I - output current of PV module,
R_s - Series resistance of cell (Ω)
R_{sh} - shunt resistance of cell (Ω)
q - Electronic charge (1.602 *10-^{19} C),
I_{sc} - light-generated current,
K - Boltzman constant (1.38 * 10^{-23} J/k),
T_k - temperature (K), n_s number of PV cells connected in series,
N_p - number of PV cells connected in parallel,
I_o - reverse saturation current which depends on the ambient temperature
m - diode factor (usually between 1 to 2);
n_s: number of PV cell in series
n_p: number of PV cell in parallel
The block diagram of the proposed model is implemented based on the mathematical equations of the PV cell and shown in Fig. 3 and corresponding I-V and P-V output characteristics of PV cell are shown in Fig. 4.

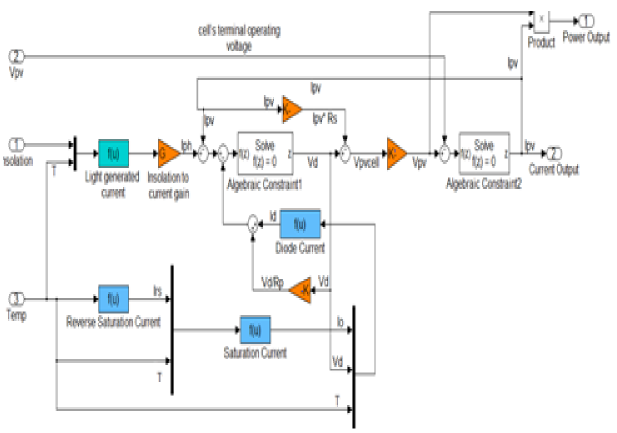

Fig. 3 - implementation of the PV model in Simulink

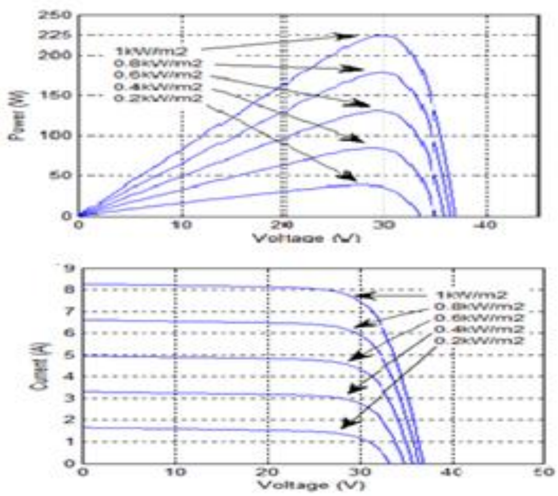

Fig. 4 I-V and P-V output characteristics

B. WIND GENERATOR MODEL

Modeling the wind energy converter is made considering the following assumptions:
Friction is neglected; Stationary wind flow;
Constant, shear-free wind flow; Rotation-free flow;
Incompressible flow (ρ=1.22 kg/m^3); Free wind flow around the wind energy converter. On the above condition the maximum physical achievable wind energy conversion can be derived using theoretical model that is independent of the technical construction of a wind energy converter. The flow air mass has certain energy. This energy is obtained from the air movement on the earth's surface determined by the difference in speed and pressure. This the main source of the energy used by the wind turbines to obtain electric power. The Kinetic energy W taken from the air mass flow m at speed v_1 in front of the wind turbines pales and at the back of the pales at speed V_2 is illustrated by equation (13)

$$W = \frac{1}{2}m({v_1}^2 - {v_2}^2) \text{ -------------(13)}$$

The resulted theoretical medium power p is determined as the ratio between the kinetic energy and the unit of time and is expressed by equation (14).

$$P = \frac{1}{2}\frac{m}{t}({v_1}^2 - {v_2}^2) = \frac{1}{2}\frac{V\rho}{t}({v_1}^2 - {v_2}^2) \text{-----(14)}$$

Where:
V- air mass volume; t- time; ρ - Air density.
Assuming the expression of the mean air speed

$$V_{med} = \frac{1}{2}(v_1 + v_2)$$

the mean air volume transferred per unit time can be determined as follows:

$$V_{med} = \frac{V}{t} = Av_{med} \text{ --------------- (15)}$$

The equation for the mean theoretical power is determined using equation (15)

$$P = \frac{1}{4}A\rho({v_1}^2 - {v_2}^2)(v_1 + v_2) = \frac{A}{4}A\rho {v_1}^3\left(1 - \frac{{v_2}^2}{{v_1}^2}\right)\left(1 - V_2/V_1\right) \text{------- (16)}$$

We can conclude that an adequate choice of v_1/v_2 ratio leads to a maximum power value taken by the wind converter from the kinetic energy of the air masses, as shown by equation (17)

$$P_{max} = \frac{8}{27} A\rho v_1^3 \text{------------- } (17)$$

This power represents only a fraction of the incident air flow theoretical power given by

$$P_{wind} = \frac{1}{2} A\rho v_1^3 \text{ --------------}(18)$$

Equations (17) and (18) leads to:

$$P_{max} = \frac{8}{27} A\rho v_1^3 = \frac{1}{2} A\rho v_1^3 = P_{wind} \cdot C_P \text{ ---}(19)$$

Where C_p represents the mechanical power coefficient which express that the wind kinetic energy cannot be totally converted in useful energy. This coefficient, meaning the maximum theoretical efficiency of wind power. The electrical power obtained under the assumptions of a wind generator's electrical and mechanical part efficiency is given by

$$P_{ele} = \frac{1}{2} C_e A\rho v_1^3 \text{ -------------- } (20)$$

Where C_e represents the total net efficiency coefficient at the transformer terminals.
The wind energy generator model was implemented by a module having configurable parameters based on the equation (20) and using the equivalent model of a generator. This model takes the following form and is shown in fig. 5

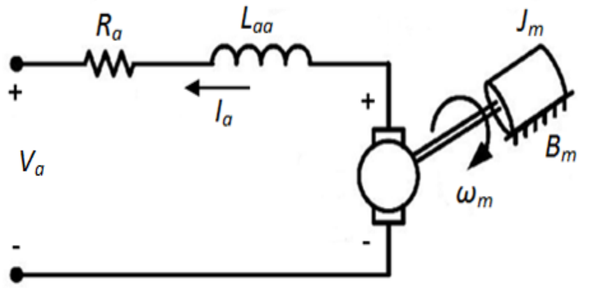

Fig. 5 Equivalent circuit diagram of a small wind generator

In the equivalent circuit diagram of a small wind generator the notations are:
R_a - rotor winding resistance
Ex - generator separate excitation winding; current I_e through this winding generates the main field
V_e - induced voltage in the rotor (armature) V- terminal voltage , Kirchhoff's voltage law, the electrical side of the PMDC generator can be presented as follows,

$$V_a = K_m W_m - I_a R_a - L_{aa} \frac{dI_a}{dt} \text{ ---------- } (21)$$

Where V_a is the generator output voltage (V), Km is the torque constant (N-m/A), ωm is the motor speed (rad/s), Ia is the armature current (A), Ra is the armature resistance (Ω), and L_{aa} is the armature inductance (H).

On the mechanical side, the electromagnetic torque (Te) developed by the DC machine is proportional to the armature current Ia, as shown below

$$Te = K_m I_a \text{--------------- } (22)$$

The applied torque produces an angular velocity ωm according to the inertia Jm and the friction Bm of the machine and load. The relations are described by

$$J_m \frac{d\,\omega m}{dt} = T_e - T_L - B_m \omega_m \text{------- } (23)$$

Where Jm is the total inertia (Kg.m^2), T_L is the load torque (N-M), Te is the electromagnetic torque (N-M), and B_m is the viscous friction coefficient (N-M-S).

The amount of power that a wind turbine can extract from the wind depends on the turbine design. Factors such as the wind speed and the rotor diameter affect the amount of power that a turbine can extract from the wind. The wind turbine was modeled using the mathematical equations.. Fig. 6 shows the wind turbine model which adopted for this study . As illustrated, there are three inputs and one output. The three inputs are the generator speed, the pitch angle, and the wind speed. The output is the torque applied to the generator shaft.

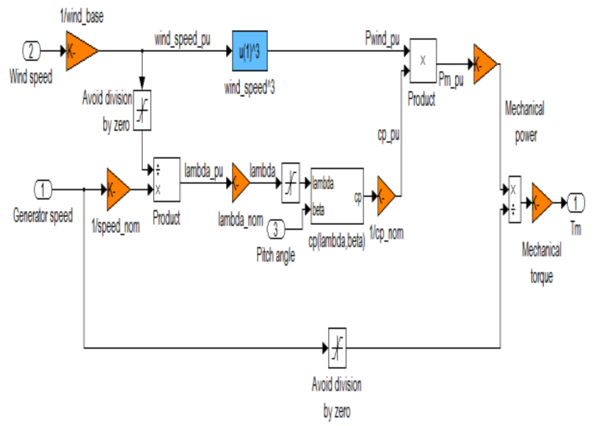

Fig. 6 implementation of the wind turbine in SIMULINK

The built-in SimPower System block model of a DC machine is used as a power generator driven by the wind turbine (MathWorks 2012). As shown in Fig. 7, the rotor shaft is driven by the wind turbine which produces the mechanical torque according to the generator and wind speed values and the Fig. 8 shows the wind turbine characteristics.

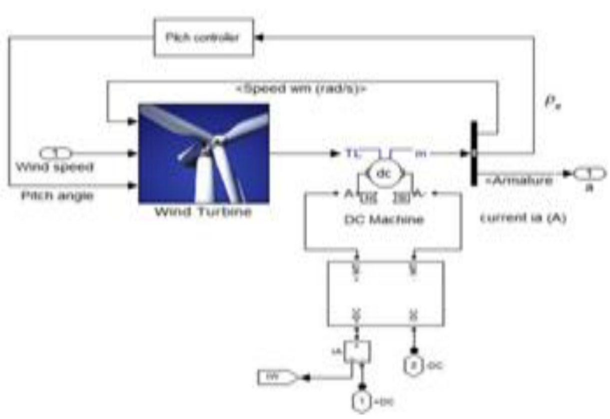

Fig. 7 Implementation of the wind turbine DC generator model in Simulink.

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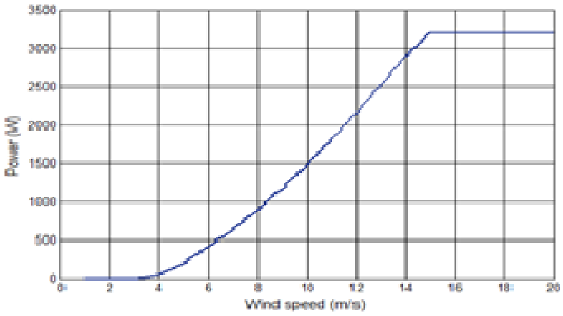

Fig. 8 wind turbine characteristics

C. BATTERY STORAGE MODEL

The battery is modeled using a controlled voltage source in series with a constant resistance, as shown in Fig. 9

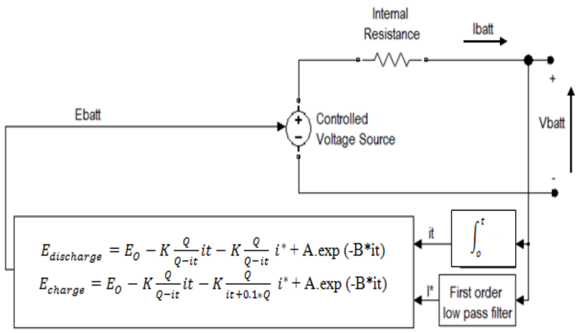

Fig. 9 Battery model equivalent circuit

1. **Discharge model:**

The Discharging battery model used is based on the Shepherd model (Shepherd 1965) but, it can represent accurately the voltage dynamics when the current varies and takes into account the open circuit voltage (OCV) as a function of state-of-charge (SOC). The OCV varies non-linearly with the SOC. Therefore, a term concerning the polarization voltage has been added $\left[K\frac{Q}{Q-it}it\right]$ to better represent the OCV behaviour.

The battery voltage (V_{batt}) obtained can be described as (Tremblay & Dessaint 2009):

$$V_{batt} = E_0 - K\frac{Q}{Q-it}it - Ri - K\frac{Q}{0Q-it}i^* + A * \exp(-B\,it) \quad \text{-----(24)}$$

Where E_o is the battery constant voltage4 (V), K is the polarization constant (Ah^{-1}), Q is the maximum battery capacity (Ah), it (∫ i dt) is the actual battery charge (Ah), R is the internal resistance (Ω), i is the battery current (A), i* is the low frequency current dynamics (A), A is the exponential zone amplitude (voltage drop during the exponential zone) (V), & B is the exponential zone time constant inverse $(Ah)^{-1}$.

2. **Charge model**

The battery charge behaviour, especially the end of the charge characteristic, is different and depends on the battery type. In Li-Ion battery the voltage will increase rapidly when the battery reach the full charge, as shown in Figure 5.4. This phenomenon can be modeled by the polarization resistance term ($K\frac{Q}{it}$). The polarisation resistance increases until the battery is almost fully charged (it = 0). Above this point, the polarization resistance increases suddenly. Theoretically, when it = 0 (fully charged), the polarization resistance is infinite. This is not exactly the case in practice. Actually, experimental results have shown that the contribution of the polarization resistance is shifted by about 10% of the capacity of the battery (Tremblay & Dessaint 2009). Hence the polarization resistance of the charge model can be described as:

$$\text{Pol Resistance} = K\frac{Q}{0.1Q+it} \quad \text{------- (25)}$$

Similar to the discharge model, the exponential voltage for the Li-Ion battery is A*exp(-Bit) term. Hence, the battery voltage obtained can be described as (Tremblay & Dessaint 2009):

$$V_{batt} = E_0 - K\frac{Q}{Q-it}it - Ri - K\frac{Q}{0.1Q+it}i^* + A\exp(-B\,it) \quad \text{----- (26)}$$

For the fully charged voltage (V_{full}), the extracted charge is 0 (it = 0) and the filtered current (i*) is '0' because the current step has just started:

$$V_{full} = E_0 - (R * i) + A \quad \text{----------------(27)}$$

In steady state the filtered current is equal to (i). Hence, the exponential zone voltage (V_{exp}) can be described as

$$V_{exp} = E_0 - K\frac{Q}{Q-Q_{exp}}(Q_{exp} + i) - Ri + A * \exp(-\frac{3}{Q_{exp}}Q_{exp}) \quad \text{---------(28)}$$

And the nominal zone voltage (V_{nom}) can be given by:

$$V_{nom} = E_0 - K\frac{Q}{Q-Q_{nom}}(Q_{nom} + i) - Ri + A * \exp(-\frac{3}{Q_{exp}}Q_{nom}) \quad \text{---------- (29)}$$

The model of the is implemented in MatLab/Simulink based on the mathematical equations. as shown in Fig. 10.

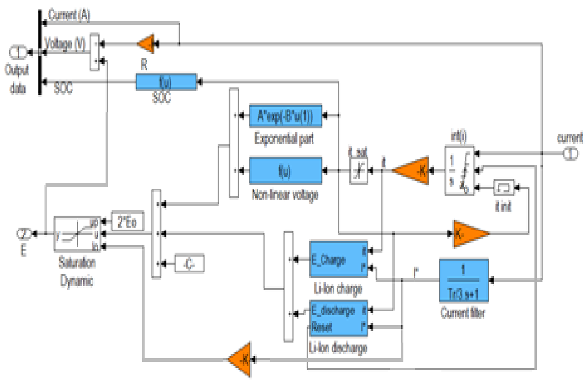

Fig. 10 implementation of the battery model in Simulink

IV. SIMULATION OF HYBRID ENERGY SYSTEM

Considering the above models, by using Matlab/Simulink an application useful for study of hybrid renewable energy system connected to a local grid was developed. Simulation model of a hybrid renewable energy system with battery storage is shown in Fig. 11.

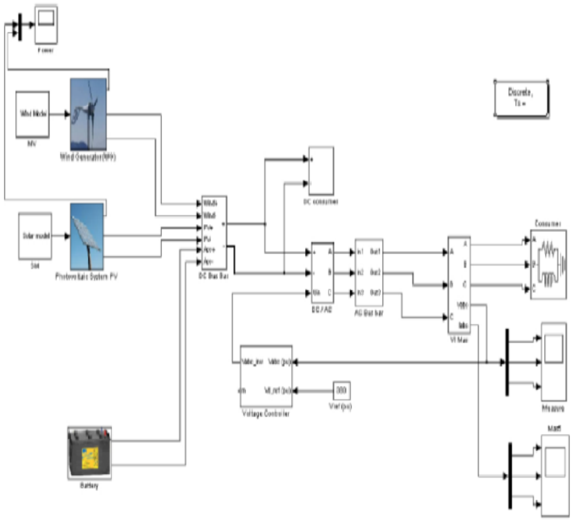

Fig. 11 Simulation model of a hybrid renewable energy system.

By using the presented simulation several functioning studies of solar-wind hybrid system can be performed. Different patterns of solar, wind models and also different type of loads can be selected. Fig. 12 and 13 illustrates the voltage waveform and current measured at the load bus bar.

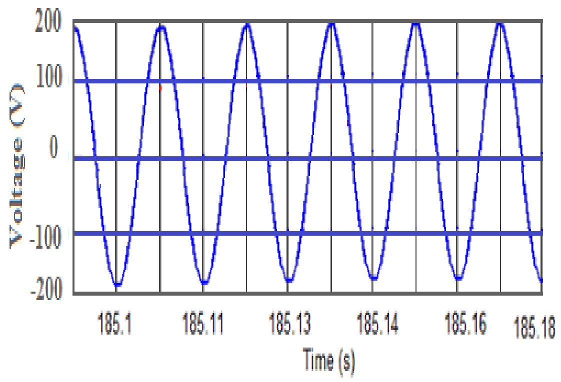

Fig. 12 Voltage waveforms at load side

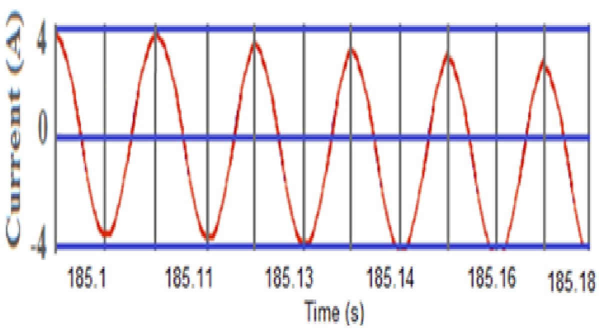

Fig. 13 Current waveforms at load side

V. CONCLUSION

This paper presented the modeling of a hybrid solar-wind energy system with battery storage using Matlab/Simulink. This application is useful for analyze and simulate a real hybrid solar-wind energy system connected to a local grid/load. The blocks like wind model, solar PV model conversion and load are implemented and the simulation results are presented. Hybrid power generation system is good and effective solution for power generation. People should motivate to use the non conventional energy resources. It is highly safe for the environment as it doesn't produce any emission and harmful waste product like conventional energy resources. It is cost effective solution for generation. It only need initial investment. It has also long life span. Overall it good, reliable and affordable solution for electricity generation

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BIOGRAPHIES

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